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# Electric Propulsion Options for Mars Cargo Missions

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## Abstract

This paper summarizes an evaluation of mission performance (in terms of vehicle mass and trip time) of solar electric propulsion (SEP) and nuclear electric propulsion (NEP) operating at power levels on the order of 1.5 $MW_e$ for Mars cargo missions. The SEP and NEP vehicles are both assumed to use lithium-propellant magneto-plasmadynamic (MPD) thrusters with an efficiency (electric-to-jet) of 60% at a nominal specific impulse of 5000 $lbf\text{-}s/lb_m$ (49 kN-s/kg); the propellant tankage factor is assumed to be 2.8%. The SEP system has a total power, power conditioning, and propulsion system specific mass of 13.6 $kg/kW_e$ with a power conditioning system efficiency of 89.6%. The NEP power system uses an SP-100 reactor with dynamic power conversion (Rankine). Two technology levels were considered for the nuclear-electric power system; the baseline system employs refractory-metals components consistent with the nominal SP-100 design. This system has a total power, power conditioning, and propulsion system specific mass of 24.8 $kg/kW_e$ with a power conditioning system efficiency of 90.2%. The second nuclear-electric power system operates at a lower temperature to allow the use of non-refractory metals components; this system has a total system specific mass of 48.0 $kg/kW_e$ (with the same power conditioning system efficiency as the refractory-metals system). The baseline refractory-metals NEP system has a lower initial mass in low Earth orbit (IMLEO) and shorter trip time than the non-refractory NEP system, but the non-refractory NEP system has a potential cost and schedule advantage over the refractory-NEP system because refractory metals need not be developed and tested. At a given "bus" power level, the SEP system has a somewhat lower IMLEO and longer trip time (due in part to the reduction in power as the SEP vehicle moves away from the sun) as compared to the refractory-metals NEP system. Interestingly, if the total "bus" power level of the SEP system is increased to give it an IMLEO comparable to that of the refractory-metals NEP system, the SEP system can have a shorter trip time, reflecting the benefit of the lower total system specific mass of the SEP system.

## I. Introduction and Background

The objective of this study was to evaluate the mission performance (in terms of vehicle mass and trip time) of megawatt-class mid-term solar electric propulsion (SEP) and nuclear electric propulsion (NEP) vehicles for Mars cargo missions. In particular, we were interested in investigating a relatively low-power regime (ca. 1.5 $MW_e$) that is significantly lower than those that have been considered in previous studies (typically $\geq 10$ $MW_e$) for Mars missions.[1] Lithium-propellant magnetoplasmadynamic (MPD) thrusters were used for both the SEP and NEP vehicles. Both high-temperature refractory-metals and lower temperature non-refractory metals SP-100 reactor technologies, using dynamic power conversion, were evaluated. Several previous papers have described the refractory-metals NEP vehicle power system,[2] power processing systems,[2,3] and thrusters,[2] and the SEP vehicle power conditioning systems.[4] This paper will emphasize the SEP and non-refractory-NEP vehicles, with the refractory-NEP system used as a baseline for comparison.

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## Mission Scenario

The basic mission scenario involves transporting a 90-metric ton (MT) payload, the Mars Lander Module (MLM)[3,5] from a 500-km altitude low Earth orbit (LEO) to a 6000-km altitude orbit around Mars. This orbit was selected because it is at the same altitude as Phobos. There are several potential benefits to this approach. From a science perspective, Phobos represents a likely stopover for a piloted mission because of interest in Phobos as a "Genesis rock" whose structure and composition have not changed since the formation of the solar system, From a practical point of view, "landing" the NEP vehicle in one of the many craters on Phobos (after deploying the payload in the 6000-km orbit) could provide shielding to nearby vehicles or people. Finally, power from the NEP or SEP power systems could be used to extract resources such as water from Phobos for production of propellant or other u seful materials.

A one-way (delivery) mission is assumed, with the vehicle left at Mars. Although both the SEP and NEP vehicles are initially deployed in a 500-km LEO, the NEP reactors are not started until the NEP vehicle is in a 1000-km altitude Earth orbit to ensure that, in the unlikely event of a system failure, the vehicle remains in orbit a sufficiently long time for reactor radiation to decay to acceptable levels. An cm-board chemical bipropellant propulsion system is used for the initial 500-to-1000" km NEP vehicle orbit transfer. In contrast, the SEP system begins operation directly from LEO and, thus, does not require the NEP vehicle's bipropopellant propulsion system.

For both the NEP and SEP vehicles, a monopropellant propulsion attitude control system (ACS) is used for attitude control when the MPD thrusters are not in use and for "landing" on Phobos if required. We assumed a chemical bipropellant "dual-mode" (NTO/$N_2H_4$) propulsion system ($I_{sp}$ = 330 lbf- s/1 $b_m$ ) (in which the bipropellant orbit transfer main engine fuel shares common tankage with the ACS system) for the initial NEP vehicle's orbit transfer and a monopropellant ($N_2H_4$) ACS system ($I_{sp}$ = 220 lbf-s/lb$_m$). "The total chemical propulsion system has a tankage factor of 16% (i.e., the. total "dry" mass of the chemical propulsion system is 16% of the total mass of propellant). Finally, when operating, the MPD thrusters, which are used in pairs, are gimbaled to provide the required vehicle attitude control.

## Vehicle Configuration

The overall NEP vehicle configuration shown in Figure 1 is based on the use of three SP-1OO nuclear reactor (with Rankine dynamic power conversion) power modules. The vehicle is comprised of modules that are compatible with the Energia launch vehicle payload capability (e.g., 100 MT to low Earth orbit in a 5.5-m diameter by 37-m long payload envelope).[2] The rcfracm-y-metals NEP vehicle power modules have a power output of 0.57-MW$_e$ each; the non-refractory metals NEP vehicle power modules have a power of on] y 0.31 -M We each due to the lower operating temperature of the non-refractory components.

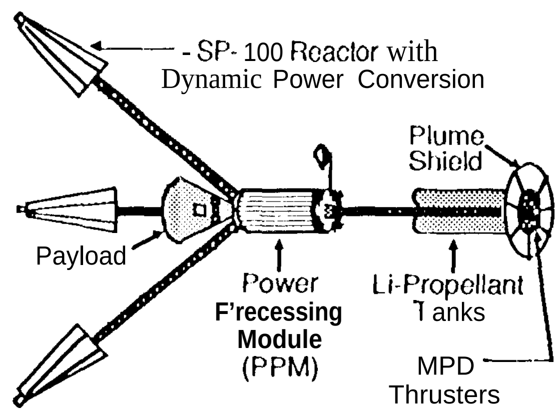


Figure 1. Megawatt-Class Nuclear Electric Propulsion (NEP) Vehicle With Li-Propellant MPD Thrusters

In this vehicle, the payload and the power processing module (PPM), which contains the power processing unit (PPU) electronics as well as the other spacecraft systems (chemical orbit raising and ACS propulsion system, guidance, navigation, control, telecommunications, etc.), are kept at a 24 m distance from the reactor and power conversion systems to minimize the radiation and thermal effects of the power system on the PPM and payload. Similarly, a 25-m distance. is used between the PPM and the lithium-propellant MPD thrusters in order to minimize contamination of the payload or the PPM radiator with condensable lithium from the thrusters' exhaust plumes. With these constraints, it is possible to package the PPM, thruster clusters, Li propellant tanks, deployable plume shield, and reactor-to-PPM and PPM-to-thruster cluster booms in one Energia launch; the three reactor and power conversion modules in a second launch; and the MLM payload in a third launch. Note that longer separation distances would be desirable; however, this would increase the boom wiring mass and resistive losses as discussed below, as well as make packaging within the launch vehicle more difficult.

A similar design approach has been followed for the SEP vehicle. For example, as shown in Figure 2, there are two solar array wings, each 37-m wide and, when un-folded, 72-m long. At a sunlight-to-electricity efficiency of 21 %, each wing produces a power of 0.75 $MW_c$ at 1 AU. The primary difference between the SEP and NEP PPMs is in the. placement of the two solar array panels on the "sides" of the PPM (rather than on the front "end" of the PPM as with the nuclear power module booms in the NEP vehicle). Also, the PPM-to-thruster boom is longer than in the NEP case (41 m versus 30 m, respectively), such that the rear edge of the solar arrays is at the same distance (25 m) from the thrusters as that of the rear edge of the PPM in the NEP vehicle. This was done so as to ensure minimal contamination of the solar arrays with lithium propellant. Finally, as with the NEP vehicle, the SEP vehicle is comprised of module.s that are compatible with the Energia launch vehicle payload capability.

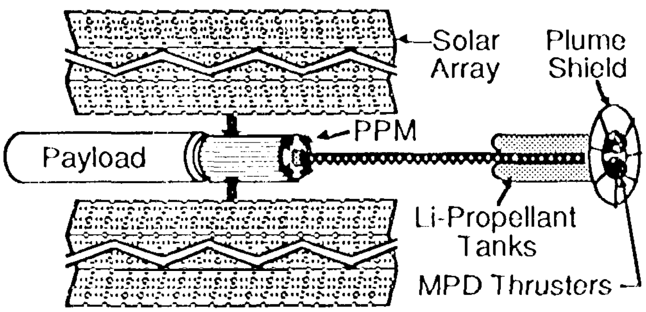


Figure 2. Megawatt-Class Solar Electric Propulsion (SEP) Vehicle With Li-Propellant MPD Thrusters

## II. Vehicle Characteristics

This section describes the vehicle characteristics, such as mass, power, specific mass, etc., that serve as input parameters to the mission analyses. For example, an electric space propulsion system consists of a power source (e. g., solar photovoltaic arrays or nuclear reactor and thermal-to-electric power conversion system), a power processing unit (PPU) which converts the power source's power output (voltage) to the form required by the thrusters, the electric thrusters, and the propellant storage (tankage) and feed systems. in terms of overall mission performance, the primary figures of merit for electric propulsion systems are their specific mass ($\alpha$), expressed in units of kilograms per kilowatt of electric power (kg/kWC,), their efficiency ($\eta$), expressed as the ratio of power output divided by power input, and the propellant tankage factor ('1'1'), defined as the ratio of the mass of the "dry" propellant tankage and feed system divided by the mass of propellant (M ). This portion of the study was aimed at a defining the power, power processing, and propulsion systems for a NEP or SEP vehicle where the total "bus" power is on the order of 1.5 $MW_c$ and the power per thruster is 0.75 $MW_c$ (i.e., two thrusters operating at any given time).

### Baseline (Refractory-Metals) NEP Vehicle

The characteristics of the baseline refractory - metals NEP vehicle have been described in detail previously.[2] They include a 90-MT payload, a combined power, power processing, and propulsion system specific mass of 24.8 $kg/kW_e$, and a total "bus" power (PC) of 1.716 $MW_c$ from three SP- 100 power modules. The power conditioning system[2,3] has an efficiency of 90.2%. The MPD thrusters[2] have an efficiency (electric-to-jet) of 60% at a nominal specific impulse ($I_{sp}$) of 5000 $lbf\text{-}s/lb_m$ (49 kN-s/kg). The thruster efficiency is assumed to be 32% at 2000 $lbf\text{-}s/lb_m$, 49% at 3000 $lbf\text{-}s/lb_m$, and 60% for $I_{sp}s \geq 4000$ $lbf\text{-}s/lb_m$. Each of the major subsystems is summarized below.

**Refractory-Metals Nuclear Dynamic Power System.** The power system uses a dynamic cycle to convert thermal power from an SP-100 reactor into electricity for use by the MPD thrusters. Three SP- 100 reactor / dynamic power conversion modules were assumed so as to be consistent with the vehicle configuration dc.scribed above. The power modules were initially sized so as to provide a net power of at least 1.5 $MW_c$ (total) to the MPD thrusters after losses in the power processing system were accounted for. As shown in Table 1, the final design resulted in a total power system specific mass ($\alpha$) of 12.2 $kg/kW_e$ with a power output from the three power modules of 1.716 $MW_c$ (0.572 $MW_c$ each) such that 1.547 $MW_e$ is supplied to the thrusters.[2]

in all cases, a maximum SP-100 reactor thermal power of 2.4 $MW_t$ and outlet temperature of 1355 K, and a minimum full-power reactor operating life of 7 years were assumed. The dynamic powei conversion system uses a potassium (K) Rankine engine with a sirlglc-shaft turboalternatoi ('l-A), with an inlet temperature of 1275 K and an outlet temperature of 849 K for a gross cycle efficiency of 2.4.5% and an overall thermal-lo-ncl electric output efficiency of 24.3%.[2]

NEP-MPD Power Processor Unit. A power processor unit (PPU) for an MPD thruster must supply voltages and currents to different elements in the thruster. In general, the PPU must provide low voltages (e.g., 1 00 V DC) at high powers (e.g., 750 $kW_e$) for the MPD discharge, and low voltages at low powers (e.g., a total of 60 $kW_e$) for components related to operation of the MPD thruster, such as the applied-ficlci MPD magnets (25 $kW_e$ pcr thruster), thruster gimbal actuators, heaters, etc., as well as for miscellaneous vehicle "housekeeping" functions.

The primary driver in (ems of NEP-MPD PPU design is the MPD thruster's requirement for low voltage and high power, which results in a requirement for high-current capacity devices (e.g., 1300 to 7500 Amps). Also, the PPU must be designed to accommodate startup and shutdown transients, and be capable of isolating thruster and PPU component failures without compromising the remainder of the power or propulsion system. '1'bus, the PPU consists of both a primary high-powc.r system and a smaller ]ow-power- power conditioning unit (PCU). For convenience, the PPU electronics components (rectifiers, filters, etc.) and switches are treated separately from the component "bus bar" wiring (both within the PPM as well as in the long booms between the PPM and the thrusters [30 m] or between the PPM and the nuclear power systems [24 m]). In fact, because of the high DC currents encountered (e. g., as much as 7500" A at 1()() V DC for the cables running to each thruster cluster), the wiring is almost two times heavier than the. PPU electronics and switches (e. g., a specific mass of 6.7 kg/k $W_e$ for the cabling versus 3.2 kg/k $W_e$ for the electronics and switches). 1 lowever, the cabling is also used to form the main structural elements for the reactor and thruster booms, thus partially offsetting the cabling mass penalty. Finally, the PPU electronics components in the PPM (rectifiers, filters, switches, etc. ) and the cabling have comparable 1osscs and corresponding efficiencies (-97%); however, because the PCU power is counted as a "loss" in the PPM component's power budget, their net efficiency is reduced to 93%.[2,3]

MPD Thruster and Propellant Tankage System. The total MPD thruster system includes the MPD thrusters, thruster gimbals, lithium (Li) propellant vaporizer and flow controller, plume shield, and Li propellant storage and feed systems. Two clusters of thrusters arc used with onc engine operating in each cluster to provide for attitude control during thruster operation. Each cluster contains 8 MPD thrusters for a total of 16 thrusters to satisfy the cumulative engine. run time. The overall specific mass of the thruster subsystem (including plume shield) is 3.2 $kg/kW_e$ with an clc.ctric-to-jet pwer efficiency of 60% at an $I_{sp}$ of 5000 $lbf\text{-}s/lb_m$.[2]

The tank design assumes the propellant to be elemental lithium; because the propellant is in the solid phase during launch to LEO, minimal tank strength is required (i. e.., only sufficient strength to contain the propellant mass as a liquid at very low pressure in space). Waste heat from the thrusters is used to melt the Li at a temperature of 181°C. Two tanks, located on either side of the 1'1'M-to-thruster cluster boom, arc used to store the total propellant required. The tanks (and thruster waste- heat transfer system) have a tankage fraction (TF) of 0.0278.[2]

Systems-Level Values. 'Table 1 shows the systems-lcvci values of the mass, specific mass, power (and losses) of the power, power processing, and thruster subsystems. In order to derive the "nominal" system parameters, we first determine.d the mass, efficiency, waste heat, volume, tankage factor, etc. for each of the major systems based on a point design using an assumed power input (e. g., 1.5 M $W_e$) or propellant mass (e.g., 50 M'J'), and then scaled the systems to correspond to the actual power available or the actual propellant mass derived from tile detailed mission analysis. This is illustrated in 'Table 1 for the calculation of power and "effective" specific mass (defined as the mass divided by the. total "bus" power, $P_e$) based on the actual specific mass and efficiency derived from a point design for each of the major systems.

Finally, the MPD lithium propellant tankage factor (TF) is 2.8%. The chemical propulsion system has a TF of 16%; the dual-mode main engine has an $I_{sp}$ of 330 $lbf\text{-}s/lb_m$ and the ACS thrusters have an $I_{sp}$ of 220 $lbf\text{-}s/lb_m$. Lastly, a mass of one metric ton is allocated for 'the miscellaneous spacecraft systems such as guidance, navigation, and control (GN&C), telecommunications, etc.[2]

Table 1. Calculation of System-Level Specific Mass and Power for the Baseline (Refractory Metals) NEP Vehicle

| Item | Actual Specific Mass (kg/kWe) | Input Power (kW) | Efficiency | Losses | Output Power (kW) | "Effective" Mass[a] (MI") | "Effective" Specific Mass[b] (kg/kWe) |
|---|---|---|---|---|---|---|---|
| Reactor & Turboalternator (TA) (Three Sets) | | | | | | | |
| Total System | 12.24 | 7068 (t) | 24.3 % | 75.7 % | 716 (e) | 21.01 | 12.24 |
| Power Conversion | | | | 5534 (t) | | | |
| Pumps, etc. | | | | 18 (e) | | | |
| TA-to-PPM Wiring (Three Sets) | | | | | | | |
| Total System | 3.68 | 1716(e) | 98.8 % | 1.2 % | 696 (e) | 6.31 | 3.68 |
| | | | | 20 (t) | | | |
| Power Processing Module (PPM) | | | | | | | |
| Total System | 3.23 | 1696 (e) | 92.6 % | 7.4 % | 1570 (e) | 5.48 | 3.19 |
| Electronics | | | | 50 (t) | | | |
| Wiring & Switches | | | | 4 (t) | | | |
| Housekeeping PCU (Electric Output) | | | | 68 (e) | | | |
| Housekeeping PCU (Waste Heat) | | | | 3 (t) | | | |
| PPM-to-Thrusters Wiring (Two Sets) | | | | | | | |
| Total System | 3.08 | 1570 (e) | 98.6 % | 1.4 % | 1547 (e) | 4.84 | 2.82 |
| | | | | 23 (t) | | | |
| Thrusters (Two Sets, $Is_p$ = 5000 $lb_f$-s/$lb_m$) | | | | | | | |
| Total System | 3.16 | 1547 (e) | 60.0 % | 40.0 % | 929 (jet) | 4.89 | 2.85 |
| | | 66 (e)[c] | | 619 (t) | | | |
| Total Vehicle[d] | (25.39) | 1716=$P_e$[d] | 54.1 % | 45.9 % | 929 (jet) | 42.53 | 24.78 |
| TA-to-Thrusters | | | 90.2 % | 9.8 % | | | |
| Thrusters | | | 60.0 % | 40.0 % | | | |

a "Effective" Mass = (Actual Specific Mass)·(Input Electric Power) except for Reactor & TA system
b "Effective" Specific Mass= ("Effective" Mass)/ (Total "Bus" Electric Power, $P_e$)
c Electric power (from Housekeeping PCU) for Thruster Magnets and Lithium Vaporizer Heaters
d Total Vehicle (less Chem. Prop., Miscl. Systems, and Li Propellant Tanks) based on Total "Bus" Electric Power, $P_e$

Non-Refractory Metals NEP Vehicle

For this study, we were interested in identifying the impact in total system mass and trip time for the situation where a near-term SP-100 reactor employing lower-temperature, non-refractory metals is used. For example, as shown below, we found that the non-refractory metals dynamic SP-100 power system has almost three times the specific mass and one-half the power-per-module of the refractory-metals system (35.5 kg/kW$_e$ and 311 kW$_e$ versus 12.2 kg/kW$_e$ and 572 kW$_e$, respectively). Also, because of its lower operating temperature and thus larger waste-heat radiator, only two of the non-refractory power modules can be packaged in the Energia launch vehicle whereas three of the refractory power modules can be delivered to LEO in a single launch. Nevertheless, even though this system has lower performance than the refractory-metals NEP system, its lower maximum temperature would allow the construction of the nuclear power system with non-refractory metals, thereby saving the time and cost associated with re-establishing refractory- metals technology.

For this analysis, the power conditioning and thruster technologies are the same as those used in the refractory-metals NEP vehicle (i.e., they will have the same specific mass and efficiencies as those described above), The non-refractory reactor and power conversion system will be discussed next.

Non-Refractory Metals Nuclear Dynamic Power System. As with the refractory-metals system, a dynamic cycle is used to convert thermal power from an SP-100 reactor into electricity for use by the MPD thrusters. The SP- 100 reactor/dynamic power conversion modules were assumed to be consistent with the overall vehicle configuration described above, although more than three power modules may need to be attached to the PPM to provide sufficient power because of the lower power per module in the non-refractory metals system. The use of non-refractory metals in the nuclear power system results in a total vehicle power, power conditioning, and propulsion systems specific mass of 48.0 kg/kW$_e$ with the same power conditioning system efficiency as the baseline NEP system (90.2%).

For the refractory-metals reactor, the SP- 100 reactor thermal power is 2.4 MW$_t$ with a reactor outlet temperature of 1355 K. For the non-refractory metals system, the 2.4-MW$_t$ reactor outlet temperature is limited to 1010 K, which is about the maximum temperature for using non-refractory metals. Both Rankine and Brayton thermal-to-electric power conversion systems were evaluated, with the Rankine system having the better performance. In the Rankine cycle, potassium's large specific volume at the lower turbine outlet temperature would lead to an unreasonably large, massive turbine. Therefore, we chose cesium as the working fluid for the non-refractory metal Rankine cycle. Because non-refractory metal is susceptible to attack by lithium, we chose to replace lithium with potassium as the reactor coolant. Finally, we assumed that changing the reactor coolant would not change the reactor mass significantly.

Overall performance parameters of system mass, specific mass, power per module, and module length (for a fixed 5.5-m diameter of the Energia cargo volume) were determined as a function of condensor temperature. The results are shown in Figures 3. A power module minimum specific mass value of 34.4 kg/kW$_e$ (with a net power output of 400 kW$_e$) and module. stowed (launch) length of 20.4 m occurs at a condensor temperature of 675 K. However, this module length is 55% of the length of the Energia cargo shroud; thus, for the mission analyses presented below, we assumed a condensor temperature of 725 K, corresponding to a stowed length of 18.3 m (to allow two power modules per Energia launch). This results in a slightly higher specific mass of 35.5 kg/kW$_e$ and a net power per module of 311 kW$_e$.

Systems-Level Values. Table 2 shows the systems-level values of the specific mass and efficiencies of the SEP-MPD vehicle power, power processing, and thruster subsystems. Because only the nuclear power system is changed from the baseline refractory-metals case, a simplified treatment of subsystem specific mass and efficiency is given.

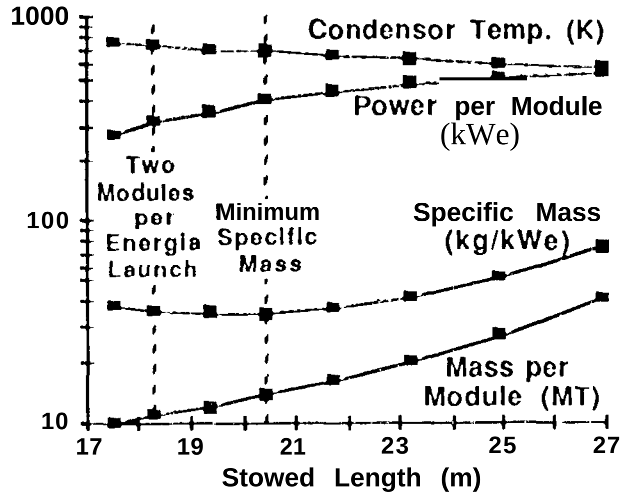


Figure 3. Non-Refractory Metals SP- 100 Power Module Characteristics

Table 2.. Calculation of System-Level Specific Mass and Power for the Non-Refractory Metals NEP Vehicle

| Item | Actual Specific Mass (kg/kWe) | Efficiency | "Effective" Specific Mass[a] (kg/kWe) |
|---|---|---|---|
| Reactor & Turboalternator (TA) | | | |
| Total System | 35.50 | --- | 35.50 |
| TA-to-PPM Wiring (Three Sets) | | | |
| Total System | 3.68 | 98.8% | 3.68 |
| Power Processing Module (PPM) | | | |
| Total System | 3.23 | 92.6% | 3.19 |
| PPM-to-Thrusters Wiring (Two Sets) | | | |
| Total System | 3.08 | 98.6% | 2.8? |
| Thrusters (Two Sets, $I_{sp}$ = 5000 lbf-s/lb$_m$) | | | |
| Total System | 3.16 | 60.0% | 2.85 |
| Total Vehicle[b] | (48.65) | 54.1% | 48.04 |
| TA-to Thrusters | | 90.2% | |
| Thrusters | | 60.0% | |

[a] "Effective" Specific Mass= (Actual Specific Mass) . (Efficiency) except for Reactor & TA system and TA-to-PPM Wiring

[b] Total Vehicle (less Chem. Prop., Miscl. Systems, and Li Propellant Tanks) based on Total "Bus" Electric Power, PC,

SEP Vehicle

The SEP system has a total power, power conditioning, and propulsion systems specific mass of 13.6 $kg/kW_e$ with a power conditioning system efficiency of 89.6%. The same thruster and tankage values assumed for the NEP vehicle.s arc also used for the SEP vehicle. The solar array and power conditioning systems arc described next.

SEP Power System. The solar arrays are assumed to have a specific mass of 10 $kg/kW_e$ (exclusive of cabling, which is treated separately in the PPU system). Two modules arc used; for a nominal width of 37 m (to be compatible with the Energia cargo shroud) and a sunlight-to-electricit y efficiency of 21%, each 750-kWc panel has an unfolded length of 72 m. No specific solar array technology was assumed, although the specific mass given is typical of advanced APSA-type arrays. Several array technologies could be used to meet both the specific mass and packaging requirements, including APSA, inflatable, or concentrator arrays.

SEP-MPD Power Processor Unit. in terms of its impacts to PPU design, the primary differences between SEP and NEP power systems lie in their voltage output. For example, the nuclear power system has a low-voltage, low-frequency, three-phase AC output from its dynamic power conversion system (which provides constant power output during the Earth-to-Mars transit) in which the power system voltage (ea. 1()() V) is matched to that of the thrusters to eliminate the need for a transformer[3] The solar array has a similar low-voltage power output, but DC, that varies with the, distance of the vehicle from the sun.

1 lowever, there arc several important differences between the NEP and S1 :P PPU systems driven by the need to appropriately condition power (e.g., rectify AC to DC) from the power systems, and by the need in both SEP and NEP PPU systems to allow control / isolation of operating, spare, and failed components in the two power systems. The control and isolation functions are accomplished with a combination of electro-mechanical switches and by solid-state rectifier/filter modules (to prevent "feedback" from, for example, variations in thruster operation into the power system). For example, the NEP PPU consists of a multiplicity of 3-phase (3-$\phi$) silicon controlled rectifiers (SCRs). They receive AC power from t urboal ternators in the dynamic nuclear power system and convert it to DC power for the thrusters. The SCRs arc also phase controlled in order to provide the various control strategies to drive the MPD thrusters (e.g., controlled current or controlled voltage strategies), and to provide. feedback isolations

The SEP PPU receives DC power from the solar array which is then fed to a DC/DC converter to condition, control, and isolate power for the MPD thrusters. The SEP PPU power controllers consist of a multiplicity of metal-oxide semiconductor- (MOS-) controlled thyristors (MCTs), diodes, and inductors. The MCTs (by their switching action) and the other associated components constitute a DC-to-DC converter and provide the required thruster current and voltage control and feedback isolation.[4]

in both the NEP and SEP PPUs, the switches used arc non-load break type electromechanical devices that arc designed to disconnect (or connect) thrusters and other components. 1 lowever, at these power levels (e.g., as much as 0.75 $MW_c$ per thruster), the switches cannot be opened/closed while under power. "1'bus, for example, in the SEP PPU, electrical power is disconnected from a thruster by first commanding the MCTs to turn off, and then by opening the non-load break thruster switch. Similarly, any one (or more) of six sub-sections in each solar panel can be isolated by first turning on an associated array MCT switch to reduce the sub-section voltage to zero by shorting. The array sub-section switch can then be opened without arcing.[4]

These requirements result in the SEP PPU electronics components in the PPM (rectifiers, filters, switches, etc.) having a specific mass of 2.1 $kg/kW_e$ and an efficiency of 97%; however, as with the, NEP PPU, the PCU power is counted as a system-level "loss," so the overall efficiency of that portion of the SEP PPU contained in the PPM is reduced to 93%.[4]

The cabling for the two nominal 750 $kW_e$ solar arrays is included in the PPU mass and power loss budge.t because they represent a significant fraction of the array's specific mass. For example, the cabling in the. solar arrays has a specific mass of 3.7 $kg/kW_e$ compared to 10 kg/kWe for the arrays (including cells, structure, etc., but not cabling). The PPM-to-thruster cabling is similar to that used in the NEP system; the primary difference is its longer length so that the solar arrays arc kept 2.5 m from the thrusters. 'J'bus, the total cabling specific mass is 9.1 $kg/kW_e$ with an efficiency of 96%.[4]

Table 3. Calculation of System-Level Specific Mass and Power for the SEP Vehicle

| Item | Actual Specific Mass (kg/kWe) | Input Power (kW) | Efficiency | Losses | Output Power (kW) | "Effective" Mass[a] (MT) | "Effective" Specific Mass[b] (kg/kWe) |
|---|---|---|---|---|---|---|---|
| **Solar Arrays (Two Sets)** | | | | | | | |
| Total System Power Conversion | 10.00 | 7143 (sun) | 21.0 % | 79.0 %<br>5643 (t) | 1500 (e) | 15.00 | 10.00 |
| **Solar Array-to-PPM Wiring (Two Sets)** | | | | | | | |
| Total System | 3.66 | 1500 (e) | 98.6 % | 1.4 %<br>21 (t) | 1479 (e) | 5.49 | 3.66 |
| **Power Processing Module (PPM)** | | | | | | | |
| Total System | 3.49 | 1479 (e) | 92.6 % | 7.4 % | 1370 (e) | 5.16 | 3.44 |
| Electronics | | | | 42 (t) | | | |
| Wiring & Switches | | | | 5 (t) | | | |
| Housekeeping PCU (Electric Output) | | | | 59 (e) | | | |
| Housekeeping PCU (Waste Heat) | | | | 3 (t) | | | |
| **PPM-to-Thrusters Wiring (Two Sets)** | | | | | | | |
| Total System | 4.02 | 1370 (e) | 98.1 % | 1.9 %<br>26 (t) | 1344 (e) | 5.52 | 3.68 |
| **Thrusters (Two Sets, $I_{sp}$ = 5000 $lb_f$-s/$lb_m$)** | | | | | | | |
| Total System | 3.16 | 1344 (e)<br>57 (e)[c] | 60.0 % | 40.0 %<br>538 (t) | 806 (jet) | 4.24 | 2.83 |
| Total Vehicle[d] | (24.33) | 1500 = $P_e$[d] | 53.8 % | 46.2 % | 806 (jet) | 20.41 | 13.60 |
| Solar Array-to-Thrusters | | | 89.6 % | 10.4 % | | | |
| Thrusters | | | 60.0 % | 40.0 % | | | |

a "Effective" Mass = (Actual Specific Mass) ·(Input Electric Power) except for Solar Arrays
b "Effective" Specific Mass = ("Effective" Mass)/(Total "Bus" Electric Power, $P_e$)
c Electric power (from Housekeeping PCU) for Thruster Magnets and Lithium Vaporizer Heaters
d Total Vehicle (less Chem. Prop., Miscl. Systems, and Li Propellant Tanks) based on Total "Bus" Electric Power, $P_e$

Systems-Level Values. Table 3 shows the systems-level values of the mass, specific mass, power (and losses) of the SEP-MPD vehicle power, power processing, and thruster subsystems. For the SEP vehicle, we again assumed a "nominal" power of 1.5 $MW_e$, and then scaled the systems to correspond to the actual power available. This is illustrated in Table 3 for the calculation of power and "effective" specific mass based on the actual specific mass and efficiency derived from point designs for each of the major subsystems. Finally, note that the SEP vehicle, unlike the NEP vehicles with their discrete integral numbers of power modules, can have a continuous range of powers by simply increasing the area of the solar array.

## III. Mission Analyses

The primary objective of the mission analyses discussed in this section is to determine the mass and trip time of the SEP and NEP vehicles when used for a Mars cargo mission in support of a separate piloted mission to Mars.

### Mission Analysis Assumptions

The primary mission requirement is to transport a 90-MT payload[2,5] from an initial 500-km altitude low Earth orbit (LEO) to a 6000-km altitude, orbit around Mars. A 150-m/s ΔV is allocated to a chemical monopropellant ($N_2H_4$) attitude control system (ACS) for maneuvering the empty vehicle in Mars orbit and to support an option of landing the NEP vehicle on Phobos after the payload is deployed.

A" one-way (delivery) mission is assumed, with the vehicle left at Mars. Also, as discussed above, the NEP vehicle's reactors are not started until the vehicle is in a 1000-km Earth orbit. A 262-m/s ΔV is required for the 500-to-1000-km altitude transfer. This ΔV (and bipropellant chemical propulsion system) is not needed for the SEP vehicle because it can be started at the initial 500 km LEO altitude.

Baseline (Refractory-Metals) NEP Vehicle

Figure 4 illustrates the trade-off in mass and trip time for the baseline refractory-me.tals NEP vehicle as a function of thruster $I_{sp}$ and payload mass.[2] The minimum baseline NEP vehicle trip time occurs at an $I_{sp}$ of 3,000 to 4,000 lbf-s/lbm whereas the vehicle mass continues to decrease with increasing $I_{sp}$. Thus, the selection of an "optimum" $I_{sp}$ will depend on the relative importance of minimizing mass or trip time. We have assumed a "nominal" $I_{sp}$ of 5000 lbf-s/lbm as a reasonable, compromise between the vehicle initial mass in LEO (IMLEO) and trip time. Under this assumption, the NEP vehicle has an IMLEO of 207 MT and a one-way trip time of 799 days with a nominal payload of 90 MT.

Non-Refractory Metals NEP Vehicle

Figure 5 illustrates the trade-off in mass and trip time for the non-refractory metals NEP vehicle. For comparison, the baseline refractory-metals NEP vehicle is also shown. The most striking result is the significantly higher IMLEO and longer trip time found for the non-refractory metals NEP vehicle. This is due to its having almost twice the overall specific mass (48.0 kg/kWe vs 24.8 kg/kWe) and one-half the power-per-module (0.31 MWe vs 0.57 MWe) of the refractory-metals NEP vehicle. For this reason, the number of power modules is treated as a variable in Figure 5, with several different values of $I_{sp}$ given for each vehicle and total power option.

As with the baseline refractory-metals NEP vehicle, the non-refractory NEP vehicle has a minimum trip time at an $I_{sp}$ of 3000 to 4000 lbf-s/lbm, with an "optimum" $I_{sp}$ around 5000 lbf-s/lbm. Interestingly, the two NEP systems can have comparable IMLEO values, but only if the non-refractory NEP vehicle is allowed to operate at low powers where its trip time is twice that of the refractory-metals system. Finally, as with the base.line NEP system, the payload mass (90 MT) represents a significant fraction of the total vehicle IMLEO. Thus, one approach to avoiding the serious integration issue of using the large number of nuclear power modules required for the non-refractory NEP vehicle to achieve trip times comparable to the baseline NEP vehicle would be to use several vehicles, each transporting smaller payloads. (This would, however, still result in a significant overall IMLEO for the "fleet" of vehicles.)

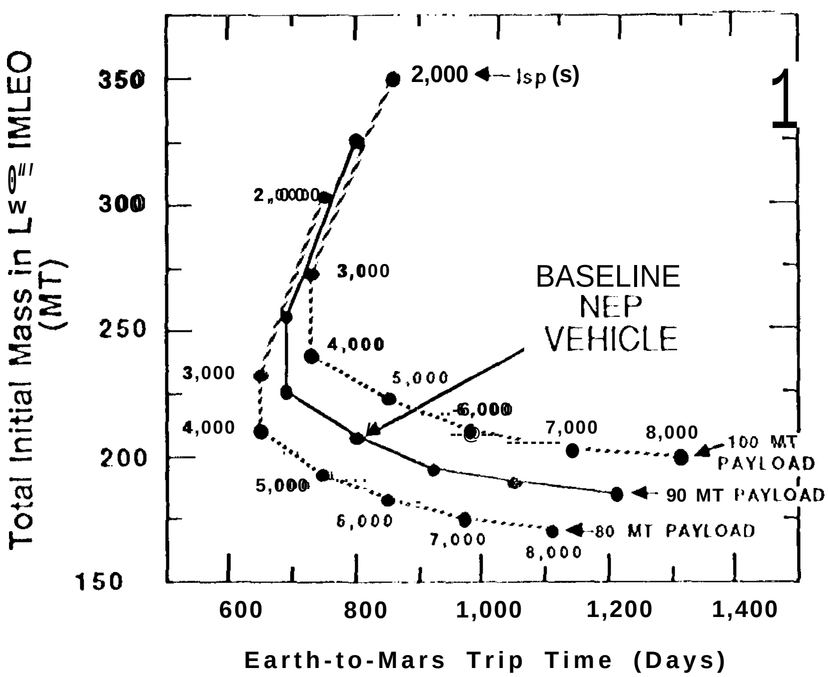


Figure 4. Mass vs Trip Time for the Refractory- Metals NEP Vehicle for the Mars Cargo Mission

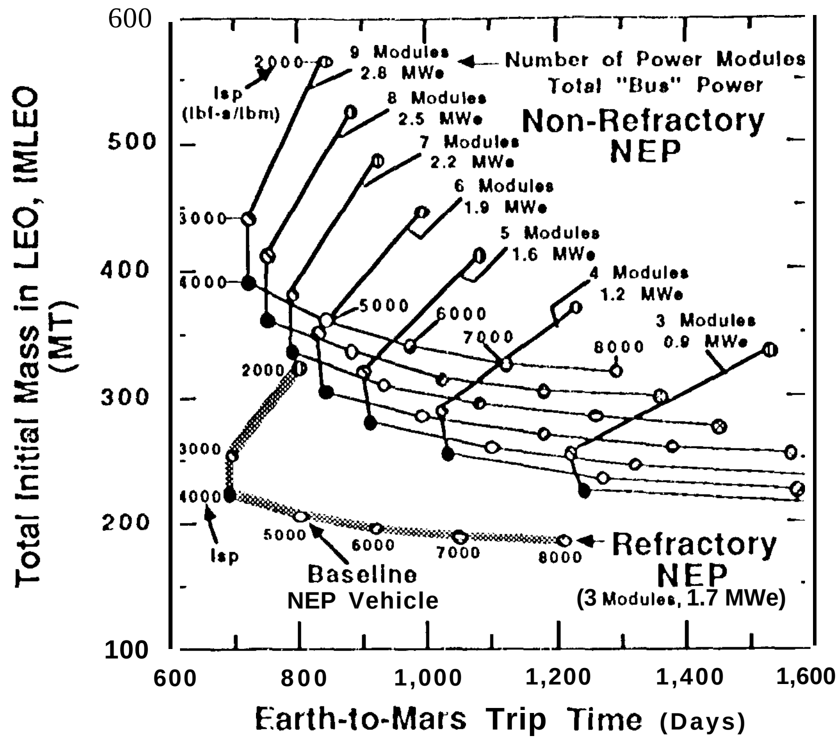


Figure 5. Mass vs Trip Time for the Non-Refractory Metals NEP Vehicle for the Mars Cargo Mission (Payload = 90 MT)

However, it should be noted that the primary advantage of the non-refractory NEP system is its potential for an overall development cost and schedule that is significantly less than that of a refractory-metals NEP system. Specifically, the use of non-refractory metals eliminates the time and cost associated with re-establishing refractory metals technology (e. g., the capabilities for refractory alloy machining and welding that existed in the U.S. in the 1960s), and with conducting all development and performance tests in a vacuum environment (because of the corrosion of refractory metals by oxygen at operating temperatures).

It is beyond the scope. of this paper to quantify in detail the potential cost and time savings realized by using non-refractory metals technology for the reactor and dynamic power conversion system. However, based on our previous work[2] in estimating development and test requirements for a refractory-metals NEP system, we can identify areas where there could be substantial savings. For example, there is a period of 2 years required for reactor test facility preparation. For the dynamic power conversion system, there is a 1-year components test facility preparation period, and a 1.5-year for preparing facilities for full-up engine testing. Thus, there exists the potential for reduction of test facility preparation cost and schedule, and later cost savings during facility operation, due to the ability to test under non-vacuum conditions with non-refractory metals components and systems.

SEP Vehicle

Figure 6 illustrates the trade- off in mass and trip time for the SEP vehicles compared to the baseline refractory-metals NEP system for the Mars cargo mission. For a given initial "bus" power, SEP vehicles generally have a longer trip time than a comparable refractory-metals NEP vehicle because of the decrease in power as the SEP vehicle moves away from the sun. For example., at a nominal 1.7 MWC power level, the SEP vehicle has a 76-day longer trip time than the refractory NEP vehicle, although there is a 24 M-l' mass savings (due in part to the slightly lower specific mass of the SEP system, but mostly to the lack of the 19-M-1' orbit-raising bipropellant system required by the NEP vehicle.). Also, as discussed earlier, the NEP power modules supply power in discrete, integer numbers of power modules; by contrast, the SEP system can be designed with arbitrary (i.e., non-integer unit) amounts of power. For example, for an SEP system at a power level that gives the same trip time as the refractory NEP vehicle (799 days), the SEP system saves 11 MT in IMLEO.

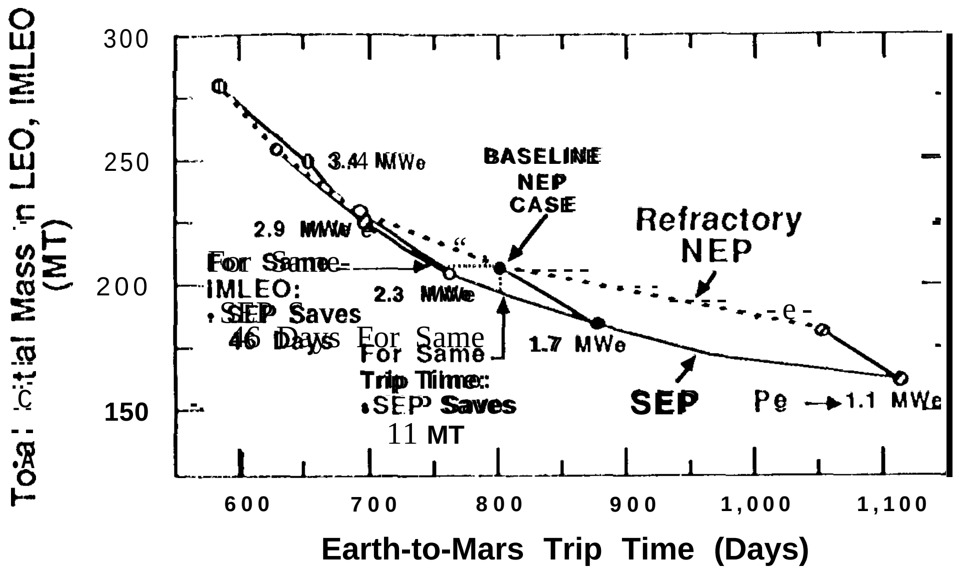


Figure 6. Baseline Refractory -NEP vs SEP for the Mars Cargo Mission (Payload = 90 MT, $I_{sp}$ = 5000 $lb_f$-s/$lb_m$)

Similarly, for the same IMLEO (207 MT), the SEP vehicle saves 46 days of trip time. However, there may be significant issues associated with packaging 2-MWe worth of solar arrays in a launch vehicle because additional volume-limited launches of solar arrays could negate the potential advantages of the SEP system. This issue should become less of a concern as the emerging technologies of concentrator arrays and inflatable structures mature.

## IV. Conclusions and Recommendations

Figure 7 summarizes the results of the Mission analyses for the refractory-metals NEP, non-refractory metals NEP, and SEP vehicles. From these analyses, we see that $MW_e$-class SEP or refractory-metals SP-100 Li-MPD NEP systems can perform Mars cargo missions with trip times of two years. MPD thruster $I_{sp}$s of 4,000 to 5,000 $lb_f$-s/$lb_m$ and efficiencies of at least 50% will be needed.[2]

One of the key requirements for achieving this level of performance in the NEP vehicle is the re-establishment of the refractory metal manufacturing and welding capabilities of the 1960s, and the preparation of vacuum test facilities for refractory-metals components and full-up systems (both nuclear and non-nuclear). In this study, we investigated the mission performance consequences of switching to non-refractory metals NEP systems. We found that the NEP vehicle performance is moderately sensitive to total specific mass; thus, the non-refractory metals NEP vehicle, with almost two times the total specific mass of the baseline refractory - metals NEP vehicle, has a significantly lower, but still acceptable, performance. Nevertheless, this lower vehicle performance may represent a favorable trade-off given the advantages of avoiding the cost and delay of requiring refractory-metals technologies.

The SEP system represents an interesting alternative to the NEP option, with the SEP vehicle having performance comparable to that of the refractory-metals NEP system. There are, however, several issues associated with the SEP system that are not encountered with the NEP systems. First, there may be difficulty associated with packaging $MW_e$-class solar arrays in a launch vehicle. Also, available power at Mars will be roughly half that at Earth; this may have an undesirable impact on the attractiveness of materials processing on Phobos if that option is pursued. The structures, dynamics, and control of large (37 m by 72 m) solar arrays may also be an issue. Finally, the large area of the solar arrays may represent a significant debris impact concern, especially because the SEP vehicle begins its long Earth-escape spiral from a relatively debris-rich 500-km LEO. (By contrast, the NEP vehicles are relatively quickly boosted to a 1000-km altitude by their on-board bipropellant chemical propulsion systems.) However, if these concerns can be addressed, an SEP vehicle remains as a viable contender for Mars cargo missions.

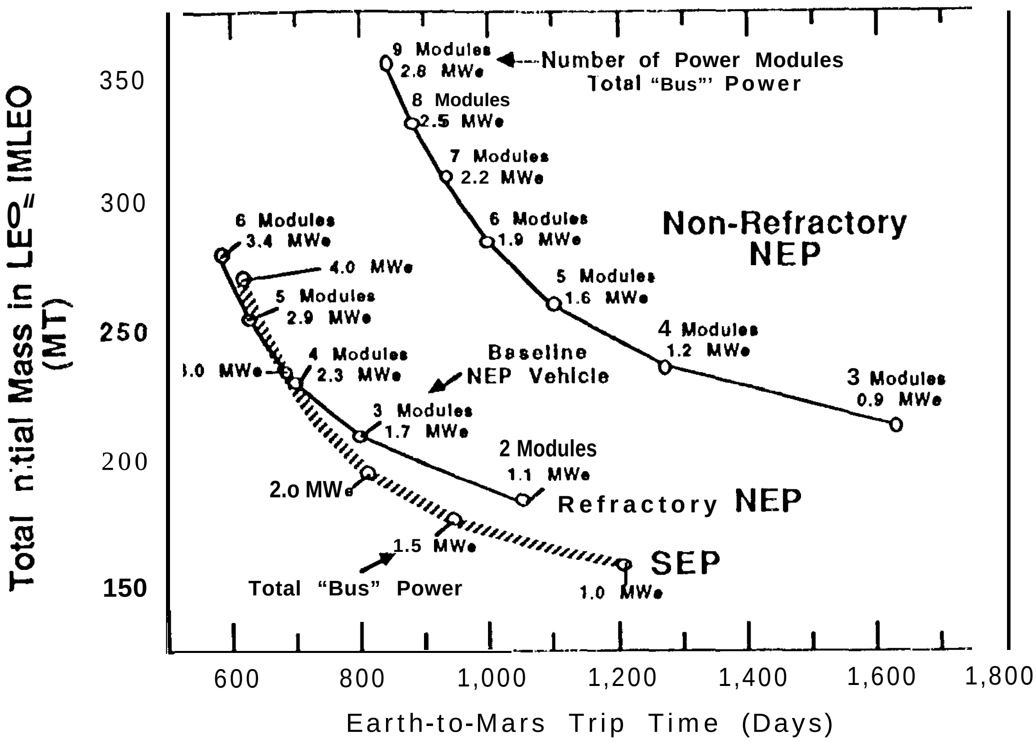


Figure 7. Comparison of Refractory NEP, Non-Refractory NEP, and SEP for the Mars Cargo Mission (Payload =90 MT, $I_{sp} = 5000$ lbf-s/lb$_m$)

For future work, we would recommend an investigation of innovative trajectory and mission designs for piloted Mars missions using the same Li-MPD SEP and NEP systems as the cargo vehicle. We also recommend an evaluation of the Russian Rankine technology effort. Finally, various technology and system design options should be evaluated, such as self-field MPD thrusters (e.g., heavier cabling due to lower voltage, but magnet mass and power eliminated), high-voltage, high frequency alternators (e.g., lower cabling mass and losses, but added transformer mass and rectifier to SSCs) for NEP power system, and various PPU configuration and technology alternatives to the systems assumed here.

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